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Internal conversion and energies of γ-lines from Co^{60}

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With 3 figures in the text

The multipole character of any γ-radiation, including the spin difference of the two nuclear levels between which a transition takes place, can be determined in several more or less indirect ways. In the case of Co^{60}, which is known to emit a soft β-spectrum ($E_{\beta\,\max} = 0.3$ MeV) followed by two γ-quantas in cascade[1] (1.1 and 1.3 MeV), the mode of disintegration gives reason to believe that both γ-radiations are of a quadrupole nature. Furthermore the angle between the direction of emission of the two quanta fits well with theory if the spin assignments 4, 2, 0, are given to the three levels involved[2], the spin 0 on obvious grounds being given to the groundstate of Ni^{60}.

Another possibility to get further information on this point would be to study the internal conversion of the γ-rays. Since the energy exchange between the nucleus and the atomic shell is also largely dependent on whether the transitions are of magnetic or electric origin a comparison between experimental values and theory will give still more detailed knowledge of the type of radiation emitted.

In the case of Co^{60} such an investigation does not look very promising at first sight since the expected internal conversion coefficients for these high energy γ-rays for such a low Z-value are found to be of the order of 10^{-4}. Furthermore, since the formulas in this energy region are not very sensitive to either multipole order or magnetic-electric type, the values of the coefficients have to be determined rather accurately to be of any use. Obviously this would not in general be possible, when the conversion lines are small compared to the continuous spectrum. In this particular case, however, the lines happen to fall well outside this spectrum and can therefore be measured without any continuous background.

Another difficulty, which has to be considered here, because of the expected small values of the internal conversion coefficients, is the effect of the *external* photoeffect in the sample itself. Since the K-absorption energies of Co and Ni differs by only 2 keV, one cannot possibly resolve two lines from each other at energies above 1 MeV, when one of them is an internal conversion line and the other an external photoline. The specific activity must therefore be so high that a reasonable counting speed on the lines is obtained with the use of such a thin sample that the external photoeffect is negligible compared to the internal effect. This thickness

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[1] M. Deutsch and L. G. Elliott, Phys. Rev. *62*, 558, 1942. M. Deutsch, L. G. Elliott and A. Roberts, Phys. Rev. *68*, 193, 1945.

[2] E. Brady and M. Deutsch, Phys. Rev. *72*, 870, 1947.

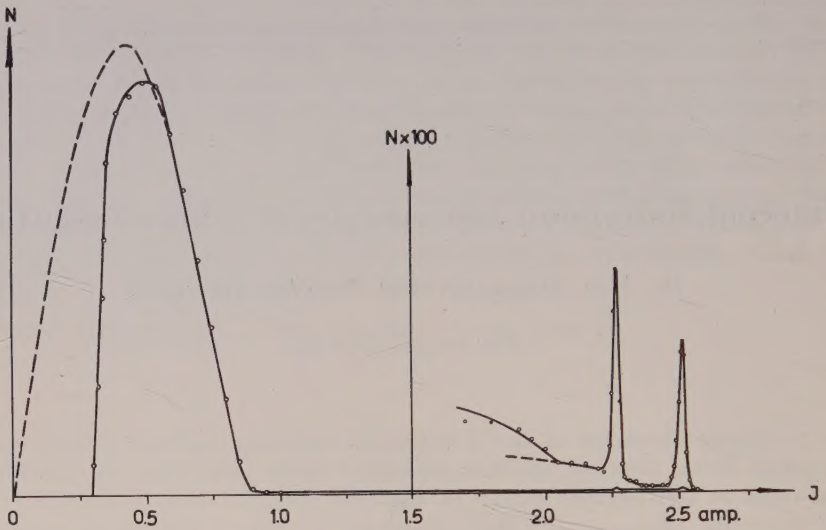

Fig. 1. Co^{60} β-spectrum with the two internal conversion lines in 100 × magnification.

can easily be computed. At the energies here concerned the cross section for external photoeffect in Co can be put at $\sim 4.5 \times 10^{-26}$ cm^2, which means a photo absorption coefficient of about 4×10^{-3} cm^{-1}. A Co sample with a thickness of 10 mg/cm^2 should therefore yield an "external photo coefficient" of maximum $\sim 0.5 \times 10^{-5}$. This thickness can evidently be allowed, as the effect is small compared to 10^{-4}. The Co sample (obtained from Oak Ridge) was strong enough to enable the use of extended sources down to a few mg/cm^2.

The investigation was performed with a large double focusing spectrometer ($\rho =$ 50 cm). The maximum transmission is about 1 % and when extended sources, as in this case, are used, the resolution will then be around 1 %. The value of the magnetic field is registered continuously by means of a rotating coil system. This consists of two coils on a common axis, one coil being in the spectrometer and the other in a Helmholz coil. The current through the Helmholz coil is adjusted for minimum current in the rotating system. This minimum is very sharp and the accuracy in the field adjustment with the present arrangement is ~ 1 ‰. This will be increased in the near future. The spectrograph was calibrated against several of ThB:s internal conversion lines (ranging from the F-line to the X-line) and the annihilation radiation (510.8 KeV).

The active Co was precipitated from a large drop (as sulphide) directly on the substratum (a thin zapon lac film). Two sources were used, one having a thickness of ~ 8 mg/cm^2 the other 2 mg/cm^2, and several independent runs were made.

The result of one investigation is seen in Fig. 1. The spectrum is given in the divided form. The continuous spectrum has its endpoint at about 0.9 amp. The counter window was about 3 mg/cm^2 and consequently cuts off an appreciable part of the low energy spectrum. Under the assumption that the spectrum has essentially an allowed form, the true form of the spectrum can easily be constructed by extrapolating the Kurie plot, obtained from points where the absorption should be small, backwards to low energies. The dotted curve in the figure has been obtained in

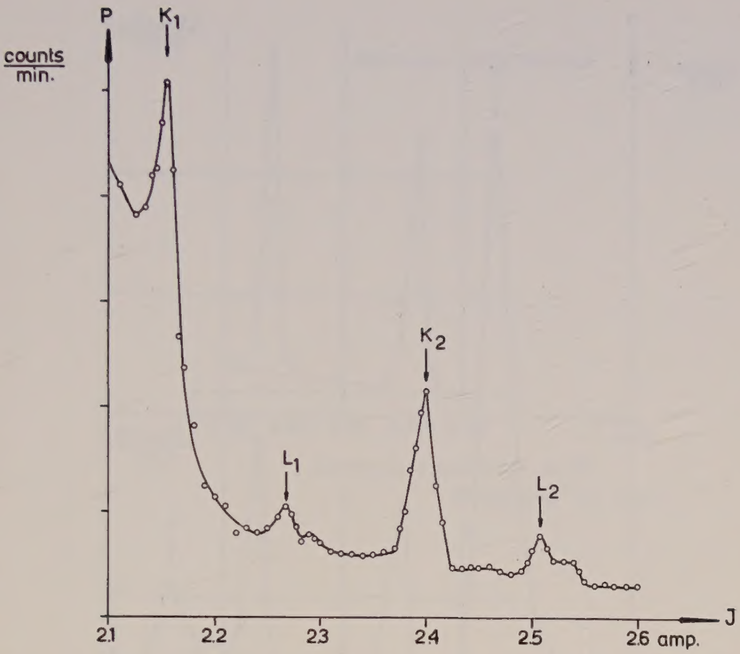

Fig. 2 a. Photo electron spectrum of the two Co^{60} γ-rays expelled from 3.7 μ lead converter.

this way. The expected error obtained with this procedure would tend to make the internal conversion coefficients too big.

Beyond the continuous spectrum a long tail of very small intensity can be noticed, containing Compton electrons expelled from the sample by the γ-radiation. The internal conversion lines appear at about 2.28 and 2.52 amp. and can just be noticed in this scale above the I-axis. The last part of the curve showing the conversion lines has been magnified 100 times and is inserted in the figure.

The sharp peaks are suitable for precise measurement of the two γ-ray energies. which might be of interest, since these γ-lines are often used as lines of reference in this energy region. For that purpose the lines obtained with the thinner source (2 mg/cm^2) were used in order to minimize the uncertainty caused by the peak shift due to straggling. In this way the γ-energies were determined to be $E\gamma = 1.177$ MeV and $E\gamma = 1.342$ MeV. Since the accuracy of the field adjustment was about 1‰ and the half width of the lines about 1.0 %, one would estimate the limitation of the definition of the peaks to be around 1‰ in $H\rho$ or a little more. The uncertainty in this kind of measurement is, however, unfortunately caused not only by the definition of the peak but also by the straggling effect in the sample, which shifts the peak to lower energies. This effect may sometimes be hard to estimate if the sample is not quite uniformly distributed. With the thicker sample ($\sim$ 8 mg/cm^2), the peaks appeared at about 1.171 MeV and 1.332 MeV. It seems likely therefore that with the thinner sample the peak shift due to straggling should not exceed more than a few promille. Taken together with other possible errors mentioned above and errors in the calibration, the energy values obtained can be given with an error of around 5‰.

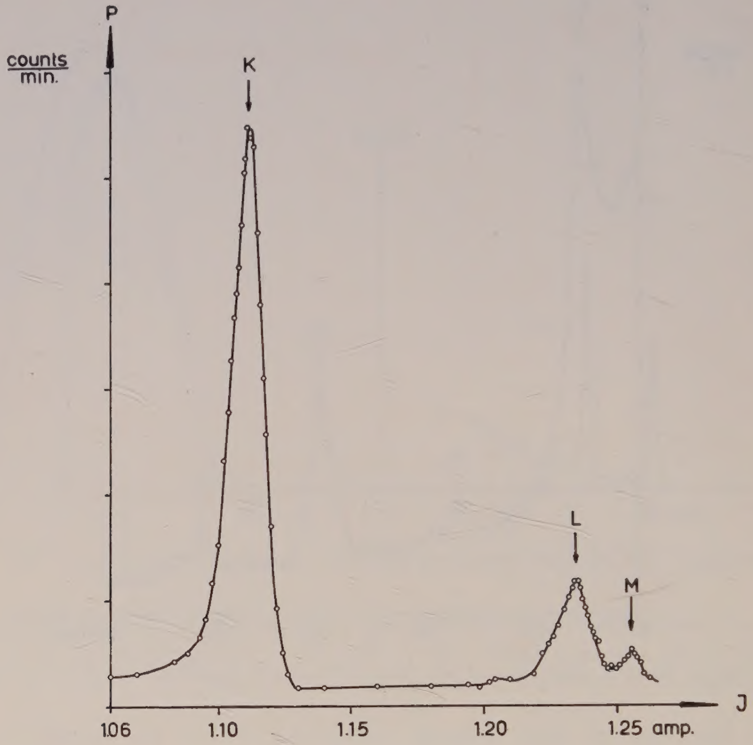

Fig. 2 b. Photo electron spectrum of the annihilation radiation for calibration.

As a further check on the energy values the Co^{60} secondary photo electron spectrum obtained from a 3.7 μ lead converter was investigated in the spectrometer. The spectrometer was calibrated under identical conditions with the same converter against the annihilation radiation (510.8 KeV). Fig. 2 a shows the photo electron spectrum or Co^{60}, showing two K-lines, two L-lines and some small indication of two M-lines. In Fig. 2 b the corresponding photo electron spectrum of the annihilation radiation is shown. In this case the resolution is more than sufficient to resolve completely the M-line from the L-line, thus providing 3 independent values of the calibration factor. These check within 2 ‰. The K- and L-lines of Co^{60} give, with the calibration factor thus obtained, the following values for the two γ-energies: 1.172 and 1.173 MeV; 1.334 and 1.337 MeV. These values are somewhat lower than those obtained from the internal conversion lines (1.177 and 1.342 MeV) but are inside the experimental errors. As final mean values we can take $E\gamma_1 = 1.174$ MeV and $E\gamma_2 = 1.338$ MeV. The errors ought to be less than 5 ‰. Recent measurements by MILLER and CURTISS[1] give the values 1.16 ± 0.03 MeV and 1.32 ± 0.03 MeV and by JENSEN, LASLETT and PRATT[2] 1.155 MeV and 1.317 MeV (± 5 ‰). These measurements were performed with thin lens spectrometers using the photo lines expelled from a lead converter.

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[1] L. MILLER and L. CURTISS, Journ. of Research of the National Bureau of Standards, 1947.

[2] E. JENSEN, L. LASLETT and W, PRATT, Phys. Rev. *75*, 458, 1949.

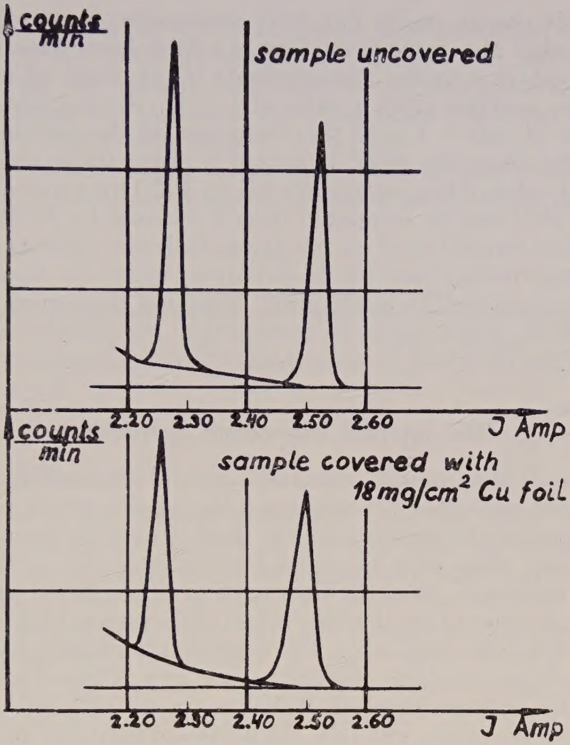

Fig. 3. Line shifts of internal conversion lines of Co^{60}, caused by a copper foil covering the sample.

Before evaluating the internal conversion coefficients from the curve it was thought advisable to prove experimentally that no appreciable number of the electrons under the peaks were due to external photo electrons. The sample was therefore covered with a 18 mg/cm^2 Cu foil and the region (above 1.5 amp) was then reinvestigated. As expected the number of Compton electrons increased. Cu has a Z-value two units higher than Co and any photo effect in the Co sample should therefore occur also in the Cu foil. One would then expect the height of the line or at least the area under the line to increase if any photo effect was of importance when the Cu foil was put above the sample. Actually the heights of the lines *decreased*. Simultaneously the lines got a little broader and these two effects very nearly compensated each other so that the areas under the lines remained essentially unchanged. In fact all features of a pure straggling effect showed up. Thus both lines were shifted to lower energies. In Fig. 3 one investigation of the uncovered and Cu covered (18 mg/cm^2) sample around the two lines is shown.

In addition one can compute from the line shifts the stopping power of the electrons in copper at these energies. The line shift $\Delta\ (H\rho)$ is 1.0 % for both lines. The stopping power I (defined as $I = \frac{\Delta\ H\rho}{0.1\ \sigma}$, where σ is the thickness of the foil in mg/cm^2) will then be $\frac{56}{1.8} = 31$. There do not seem to be any previous measurements reported on copper in this energy region but from measurements on other elements[1] one would conclude that the value found here is a little lower than one would expect. A rough interpolation between measurements on elements of smaller and higher Z-values at these energies gives a value of I ~ 35. Since a deviation of 4 units in I means an error of only ~ 1‰ in the evaluation of the distance between the unshifted and shifted lines this small departure is inside the experimental error.

The theoretical value of the energy shift ΔE (in KeV) for a copper foil of 18 mg/cm² and at $E = 1.2$ MeV can be computed from a formula by F. BLOCH[2] and is 14.5 KeV. This is the average loss of energy due to inelastic collisions. We further have to add the average energy loss due to radiation, which for these energies is very small and can be computed[2] to be 0.5 KeV. Thus, the theoretical value for the line-shift will be 15 KeV, which has to be compared to the slightly higher experimental value 16 KeV. The deviation is again inside the experimental error.

The internal conversion coefficients

The evaluation of the internal conversion coefficients from the spectrum can in principle be carried out either by comparing the heights of the peaks in undivided form or by comparing the areas under the lines in divided form. The former procedure is sufficient, when only the ratio between the two coefficients is wanted, but the latter is necessary, when the lines have to be compared with the continuous spectrum as well, in order to get absolute values of the internal conversion coefficients. Both methods have been used here. The determinations were based on several independent runs of the complete spectrum using two different samples. The mean value for the ratio between the 1.17 MeV line to the 1.33 MeV line, as measured from the heights of the peaks, was 1.26, the deviation from this value in the different determinations being only a few percent. Furthermore this value was also obtained when the line areas in divided form were compared. The absolute values of the internal conversion coefficients were:

$$\alpha_{1.17} = 2.32 \times 10^{-4}$$
$$\alpha_{1.33} = 1.83 \times 10^{-4}$$

These coefficients include the conversion in the whole atomic shell, since the resolution is not sufficient to resolve the K and L conversion lines. Before making comparisons with theoretical formulas it is convenient to correct for the contribution from the L shell. (Contributions from other shells are negligible.) At these energies the ratio between K to L coefficients is almost independent of the multipoleorder. According to HEBB and NELSON[3] this ratio is 11. The corrected K conversion coeficients are then:

$$\alpha_{K\,1.17} = 2.12 \times 10^{-4}$$
$$\alpha_{K\,1.33} = 1.68 \times 10^{-4}$$
$$\frac{\alpha_{K\,1.17}}{\alpha_{K\,1.33}} = 1.26$$

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[1] See E. RUTHERFORD, J. CHADWICK, C. ELLIS, Radiations from Radioactive Substances, Cambridge (§§ 98–100)

[2] Cf. HEITLER, The Quantum Theory of Radiation, Oxford 1944, p. 219 (5) and p. 221 (9).

[3] HEBB and NELSON, Phys. Rev. *58*, 486, 1940.

These experimental values can now be compared with theoretical ones. Relativistic calculations, valid for $Z < 30$, high energies and not too high multipole orders, i.e. calculations satisfying the present conditions, have been performed by DANCOFF and MORRISON[1]. Using very accurate wave functions ROSE and others[2] recently have recomputed α_K over a wide range of Z and $E\gamma$.

In Table I the theoretical values for α_K thus obtained have been computed in the case of $l = 1, 2, 3$ for electric and magnetic multipole radiation for the two γ-energies 1.17 and 1.33 MeV.

Table I.

Int. conv. coeff. $\alpha_K \times 10^4$

γ-energy MeV	elec. 2^l-pole			magn. 2^l-pole		experimental values
	$l = 1$	$l = 2$	$l = 3$	$l = 1$	$l = 2$	
1.17	0.74	1.58	3.17	1.24	2.93	2.12
1.33	0.60	1.17	2.11	0.97	2.13	1.68

The extrapolation of the Fermiplot obtained from the rather thick source will lead one to underestimate the number of electrons from the continuous spectrum and therefore the absolute values of the experimentally found conversion coefficients are probably too high. The best fit to theory, which can be made considering this circumstance is to assume that both γ-rays are electric quadrupole lines. The ratio of the internal conversion coefficients is much better known than their absolute values. From this fact one can under all circumstances immediately rule out a number of other possibilities, e.g. if the 1.33 MeV ray were a magnetic 2^2 pole line the other cannot be an electric 2^2 pole line etc. The theoretical value of the ratio if both transitions are electric quadrupoles is 1.35 compared to the experimentally found 1,26.

Note

Since it was thought advisable to wait for Rose's new calculations of the internal conversion coefficients the publication of the above paper has been postponed for a while. During this time new measurements of the energies of Co^{60} γ-lines have been made by D. LIND, J. BROWN and J. DU MOND (Phys. Rev. *76*, 591, 1949) with their crystal spectrometer. They obtained the values: $E\gamma = 1.1715$ MeV and 1.3316 MeV. Furthermore E. JENSEN, L. LASLETT and W. PRATT (Phys. Rev. *76*, 430, 1949) have revised their values given earlier in this paper to be instead $E\gamma = 1.169$ MeV and 1.331 MeV. The mutual agreement between the three measurements made by very different types of apparatus is now satisfactory.

SUMMARY

The internal conversion lines of the two hard γ-lines in Co^{60} have been investigated in a large double focusing spectrometer. A new determination of the γ-energies yields the values $E\gamma = 1.174$ MeV and $E\gamma = 1.1338$ MeV. The stopping power in copper for the electrons from the lines have been measured. The K-internal coversion coefficients for the two lines are $2.12 \cdot 10^{-4}$ and $1.68 \cdot 10^{-4}$. The best fit to theory is to assume that both γ-rays are electric quadrupole lines.

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[1] S. DANCOFF and P. MORRISON, Phys. Rev. *55*, 122, 1938. Formulas (18) and (19).

[2] Personal communication.

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Uppsala 1950. Almqvist & Wiksells Boktryckeri AB